THE ASTROMETRIC IMAGING TELESCOPE: DETEC'TION OF PLANETARY SYSTEMS WITH IMAGING AND ASTROMETRY

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ABSTRACT

The Astrometric Imaging Telescope (AIT) is a proposed spaceborne observatory whose primary goal is the detection and study of extra-solar planetary systems. It contains two instruments that use complementary techniques to address the goal. The first instrument, the Coronagraphic Imager takes direct images of nearby stars and Jupiter-size planets. It uses a telescope with scattering-compensated optics and a high-efficiency coronagraph to separate reflected planet light from the central star light. Planet detect ions take hours; confirmations occur in months. With a program duration of about 2 years, about SO stars are observed. The second instrument, the Astrometric Photometer, shares the same telescope and focal plane. It uses a Ronchi ruling that is translated across the focal plane to simultaneously measure the positions of each target

hundreds of stars. Enough stars of several spectral types are observed to obtain a statistically significant measurement of the prevalence of planetary systems. This observing program takes about 10 years to compl etc. The combination of both instruments in a single telescope system results from a number of innovative solutions that are described in this paper.

1. Introduction

Planetary systems are thought to commonly occur around stars like the Sun. If this hypothesis is correct then the fact that no other planetary systems are known is due only to our inabil it y to detect them with current astronomical observatories and instruments. A major goal of the new NASA program, Toward Other Planetary Systems (TOPS), is to develop the instruments and make the observations to detect, characterize, and study other planetary systems (Burke *et al.* 1992).

The new instruments must feature both an increased sensitivity to the presence of planets around nearby stars and the capability to perform a broad survey of stars so that even an unlikely null result is statistically significant. 'l'he Astrometric imaging Telescope (AIT) is a space-based observatory designed to fulfill these requirements. It consists of two instruments that use different techniques, imaging, and astrometry, to obtain complementary data on planetary systems. In the following sections wc will describe the AIT instruments, observations, and a mission and flight system designed to accommodate the instruments and fulfill the 'l'O1'S goals.

2. Instruments and Observations

2.1 IMAGING INSTRUMENT

The AIT imaging instrument is the Coronagraphic Imager (Cl). It consists of a hybrid coronagraph and a CCD camera operating in the visible range. The coronagraph uses graded occulting masks to reduce the diffracted light in the wings of target stars by at least a factor of 1000. A laboratory version of the coronagraph has demonstrated this performance. To take advantage of this coronagraph AIT features a "scattering-compensated'(optical system that reduces scattered light by the same factor in the small-angle regime. Sub-scale mirrors have been fabricated that demonstrate the performance required by AIT. These capabilities of the Al'I'/Cl arc unprecedented in a orbiting telescope but are technologically mature as shown by the laboratory verifications.

Other important AIT/CI features have been proven in past space programs. For example, the stability required by the AIT telescope pointing control system to keep the target star on the occulting mask during observations has been demonstrated in orbit. Similarly CCD imaging cameras are. known to work well in space.

The CI can detect planets in the imperfect world of the space environment. Models of CI results in the presence of effects such as pointing jitter and pixel ization, have shown it can perform successfully. Models have also shown that the coronagraph controls telescope aberrations just as it controls diffraction (Ftaclas et *al.* 1992) allowing performance goals to be met. Another paper in this volume describes the Cl in further detail (Terrile *et* al. 1993).

2.2 IMAGING OBSERVATIONS

The CI detects Jupiter-size planets around nearby stars by imaging the region within a couple of arcseconds of the stars. The hybrid coronagraph and the scattering-compensated optics reduce the light from the star so that the reflected light from the planet is no smaller than 1% of the residual starlight at the planet's position. Planets are detected from the CCD images in less than 10 'hours of observations each.

With the AIT 1.5 m-diameter primary mirror the CI detects Jupiter-size planets around approximately 50 target stars. The number of potential targets for planetary imaging increases sharply with primary diameter. With a larger primary, not only does the number of planetary photons increase as the diameter squared, but also the stellar background decreases due to the smaller diffraction spot size.

Each target is observed several times per year. If a detection is made, a confirmation will occur in several months when the star field is reobserved to eliminate spurious background objects, Color photometry of detected planets is performed with filters over periods of days. The entire observing program is completed in about 2 years.

imaging yields the following information: the planet brightness (albedo/size), star-planet separation, multiplicity of planets, and orbital phase, Prominent spectral bands may be detected via filter photometry. Orbital data is also available, but in this case, over orbital period time scales. The detection and study of circumstellar material including proto-planetary disks are other TOPS 1 goals that are accomplished with the Cl.

2.3 ASTROMETRIC INSTRUMENT

The Alrl' astrometric instrument is the Astrometric Photometer (AP). It consists of a high-precision Ronchi ruling and several photometric detectors operating in the visible range. 'l-he ruling is moved across the field of view at the telescope focal plane and its thousands of transparent and opaque line pairs modulate the light from a target star and 2S reference stars. Movable optical fibers are positioned to capture the light from each star and direct it to photon-counting, detectors from which the stellar signals are extracted. The relative phases of the target star signal and the reference star signals give an accurate determination of the target position in one dimension. Later an orthogonal measurement is made by rotating the ruling 90 degrees.

The fundamental metric in the AP is the Ronchi ruling. Errors in the ruling line edge positions limit the accuracy of the phase measurements. If the line edge errors are randomly distributed then measurement accuracy improves with the square root of the number of edges. For the AP 2S00 lines with random errors of amplitude 50 nm result in an overall accuracy of 1 nm. This corresponds to an accuracy of 10 μarcsec in the target positions, Systematic errors in the line edges do not average down and are thus only tolerable at the final required accuracy. Laboratory tests of currently available rulings have demonstrated that the random ruling line edge errors are within the required accuracy. Further tests using Moiré techniques and laser metrology are underway to measure the systematic errors.

Other sources of error include spacecraft pointing jitter, contamination of optical surfaces, and telescope aberrations. "l-he relative nature of the measurements and the modulation of the stellar signals at the ruling frequency reduce much of the effect of pointing jitter. The telescope optics are designed to be tolerant of contamination and aberrations so that astrometric performance is not compromised by errors such as secondary mirror tilt, decenter, and defocus. Another paper in this volume considers many of these error sources and shows how the required astrometric accuracy is achieved in a realistic end-to-end model (Shaklan *et al.* 1993).

2.4 ASTROMETRIC OBSERVATIONS

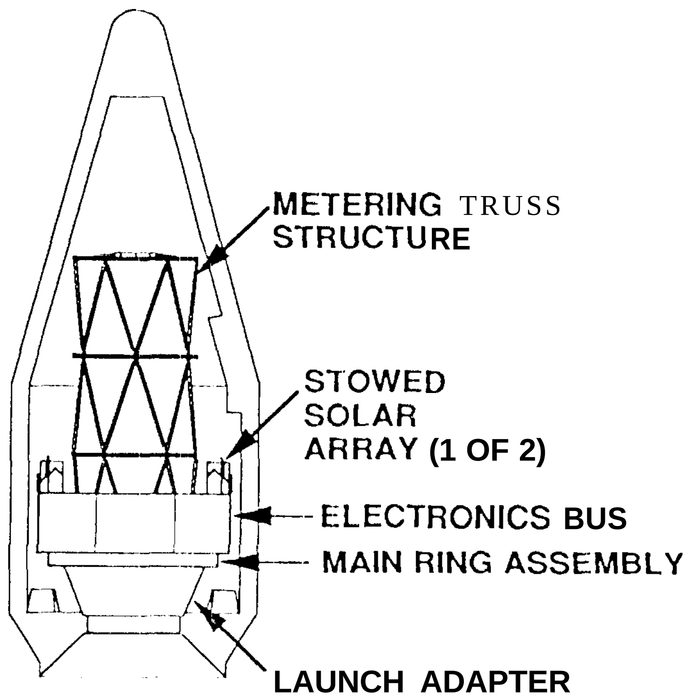
The AP is designed to detect Uranus-mass planets around hundreds of nearby stars. The RGO (Woolley *et al. 1970)* and Gliese (1969) catalogs contain more than 2000 candidate stars within 25 pc. About 800 of these stars are suitable AP targets since Uranus-mass planets would cause stellar wobbles larger than 10 μarcsec with orbital periods of less than 10 years, the nominal AIT mission lifetime. The target stars range in spectral type from A to M, with significant numbers of G (89), K (276), and M (350) stars. With hundreds of stars observed the statistics of planetary systems are determined. A statistically significant null result (no planetary systems) presents a major problem for the current theory of planetary system formation.

Each AP observation achieves 10 μarcsec accuracy in 30-60 minutes. Targets are observed several times each year and must be followed over at least an orbital period, in most cases. The astrometric program is completed after about 10 years.

Astrometry yields the following information: the planet to star mass ratio, orbital elements, planet multiplicity, and star distance (from parallax).

3. Spacecraft and Mission

The size of the AIT spacecraft is driven by two considerations. First, the number of imaging targets suitable for planet detection is a strong function of the diameter of the primary mirror



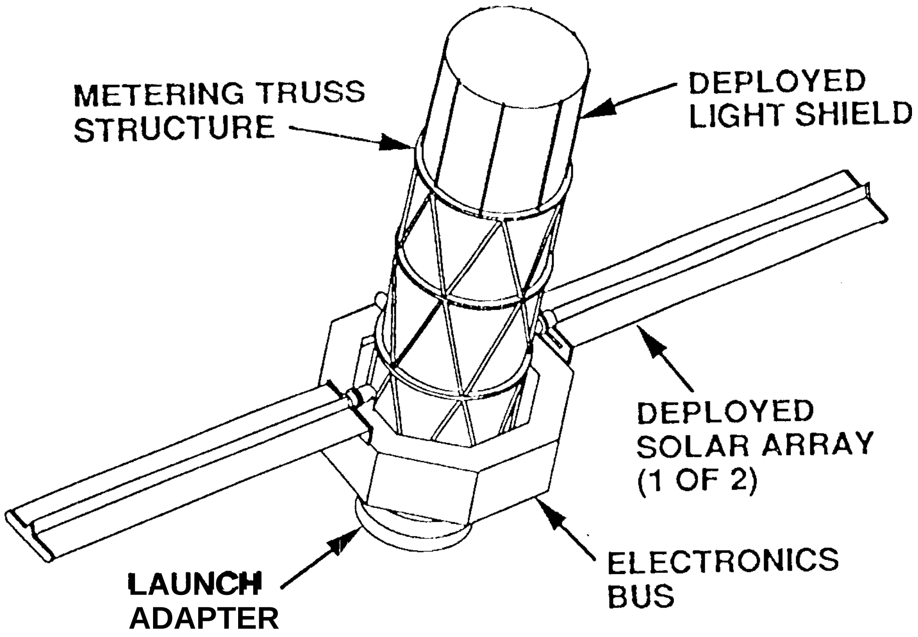
AIT LAUNCH CONFIGURATION
ATLAS IIAS FAIRING

Figure 1.

(see Section 2.2). Thus the largest diameter primary within the constraints is chosen. Second, the "distortion-free" design for the astrometric investigation (see below) pushes the optical design toward larger primary-secondary mirror separation. For best performance the AIT optical system is both wide and long.

The AIT launch vehicle, the Atlas II rocket, provides a fairing into which the spacecraft fits. Figure 1 shows AIT in the stowed position in the Atlas fairing. The primary mirror is located near the main ring assembly. A metering truss connects to the secondary mirror support structure and holds it in place with respect to the primary. The secondary mirror is located at the end of the spacecraft toward the tapered part of the fairing. Instruments are packaged behind the primary and in front of the launch adapter.

In this design solar arrays and a sun shield are deployed in orbit after the fairing has been jettisoned. The solar arrays provide the power required for spacecraft and instrument operations. 'l'he sun shield prevents sunlight and earthlight from shining on the secondary mirror, both to eliminate stray light and to better control the thermal environment. Thermal control of the optical bench and focal plane is accomplished passively with multi-layer insulation and actively with heaters. The electronics bus contains all or parts of other spacecraft subsystems such as command and data handling, telecom, and attitude control. Figure 2 illustrates AIT in the flight configuration.

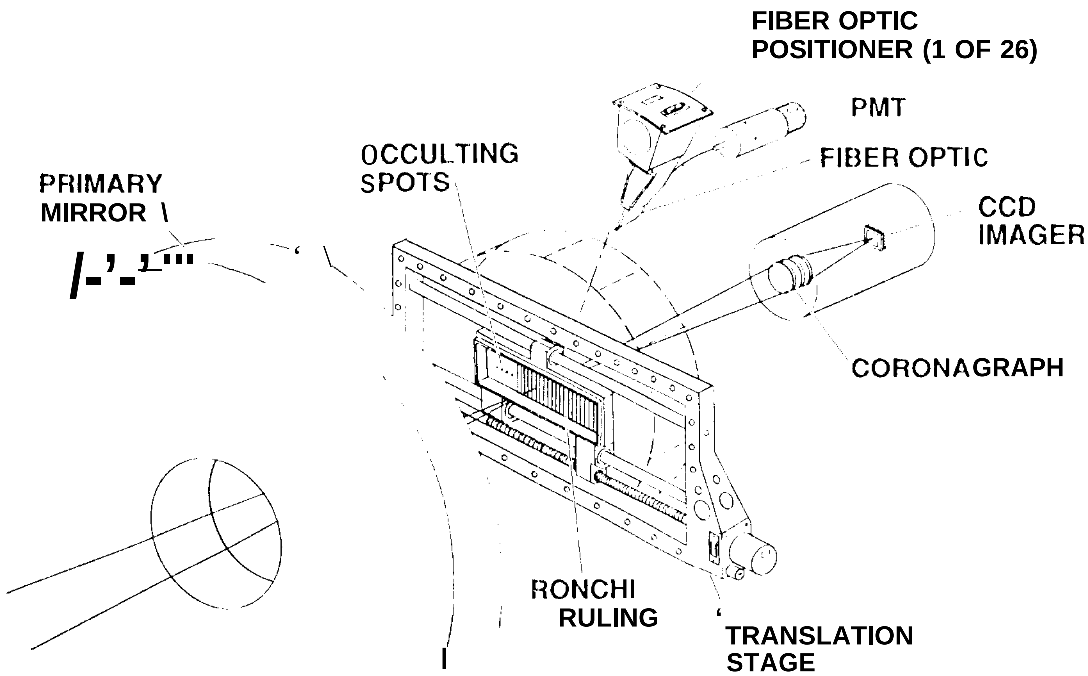


AIT FLIGHT CONFIGURATION

Figure 2.

The orbit is chosen to be a 700 km altitude, sun-synchronous, polar orbit, again to better control the thermal environment. At 700 km the orbit will not decay significantly within the 10 year nominal mission. The South Atlantic Anomaly radiation zone is at a minimum at this altitude. At higher altitudes the size and intensity of the radiation zone increases resulting in both decreased observing times and increased radiation damage to the spacecraft and instruments. The Atlas launch vehicle is incapable of placing a payload such as AIT above the radiation zones and into high Earth orbit.

Imaging and astrometric observations are performed in series. Figure 3 illustrates the AIT focal plane. Both the Ronchi ruling and the occulting masks are on a common translation stage. For AP observations the ruling is moved back and forth over the field of view with a frequency of 10-100 line pairs/s. The optical probes are placed behind the ruling at the star positions and direct the starlight to the detectors. Spacecraft pointing stability during an observation of 0.3 arcsec reduces this source of measurement error to an acceptable level (see also Shaklan *et al.* 1993).



AIT FOCAL PLANE

Figure 3.

For CI observations an occulting mask is placed on the optical axis. The AP optical probes are removed from the center of the field of view allowing the light of the target star and planet to reach the coronagraph and CCD camera. These observations require spacecraft pointing stability of 0.01 arcsec. The translation mechanism is designed to return to the imaging position in case of failure so that imaging observations could continue.

'l'he AIT optical design accommodates both instruments, 'l'he AI' requires a "distortion-free" optical system (Korsch 1989). This insures that the astrometric measurements are insensitive to changes in the optics due to in-orbit effects such as the contamination of optical surfaces or mirror misalignments. These designs generally perform better with longer focal lengths or larger mirror separations. In addition, a family of such designs exists which can be parametrized by the ratio of secondary to primary mirror diameters, 'l'he larger this ratio, the more tolerant the system is for the Al'.

The CI makes less demands on the optical design but is photon-] imited. "l'he imaging investigation prefers a smaller secondary which results in a smaller central obscuration and larger effective collecting area. The AIT telescope with a mirror diameter ratio between 0.25-0.5 is thus a compromise between the instrument requirements.

For both instruments the telescope is rolled after an observation and data is then taken in the rolled orientation to eliminate instrumental effects such as a fixed speckle pattern. For the AP observations are made in orthogonal directions. Observing constraints such as Sun- and Earth-avoidance and the South Atlantic Anomaly arc expected to reduce the observational duty cycle to no more than 50%. The instrument data rates are less than 1 Mbps. Onboard data storage capacity is about 16 Gigabits of solid state memory. In the current design data is telemetered to the 26 m Deep Space Network antennas on the ground with a maximum rate of 5 Mbps.

The science teams then analyze. the data. Imaging data may reveal the presence of Jupiter-size planets within hours. Asymmetric discoveries take longer with shorter period planets detected first. Since the planet asymmetric detectability increases with orbital period (all other things being equal) it is interesting to note that the AP has sufficient sensitivity to detect even low period planets. Table 1 shows the number of target stars from the catalogs for which a Uranus-mass planet would be detected as a function of the orbital period. At the end of the nominal ten year mission an inventory of circumstellar material, planets, and planetary systems is compiled.

Table 1

Number of Stars Observed vs. Orbital Period

Period (Years)	**Stars**
1	62
2	67
3	72
4	74
5	90
6	89
7	89
8	89
9	86
1()	80

4. **Summary**

'he Astrometric Imaging Telescope is designed to definitively address the question of the existence and prevalence of other planetary systems. It provides complementary data from two instruments which offer both images of other planets and a statistically significant survey of nearby stars. It is a technological] y feasible and operational y robust mission.

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